# Phase III NASA REPORT (draft)

# HEAXPOD PROJECT

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## 1. Introduction

Our mission has been to determine the feasibility of building a low-cost stabilization & positioning system using hexapod technology. In this Phase III of the project, we concentrated our efforts on two separate issues that affect this study. The first issue was to determine how best to control the position of the hexapod. We determined that the H-Bridge was most efficient internal control circuitry. The second issue was to find a true INS (Inertial Navigational System) that would give us all three (3) inertial angles in either a stationary position or moving platform. We decided to use the 3DM-G INS device produced by MircoStrain.

## 2. Overview

Our goal is to build a low-cost stabilization and positioning system. This system is based upon hexapod technology, data from an Inertial Navigational System (INS) device and internal control circuitry.

> Hexapod - A mechanical positioning device that moves and controls six telescopic (6) legs that are attached at opposite ends to flat circular plates. The six (6) legs operate between the two flat plates and a servomotors control each leg. Typically, hexapods are used for positioning machinery.
>
> INS (Inertial Navigational System) - A device that includes micro- circuitry and processors that outputs three (3) inertial angles roll, pitch and yaw based upon reading from internal accelerometers, gyroscopes and magnetometers. Typically, an INS is used to pick up the angular orientation of an object in space relative the earth.
>
> GPS (Global Navigational System) – A device that locates the position of an object based upon the signal from several satellites that are referencing the fixed stars.

In our application, we developed software to receive and convert angular data from the INS into useful information that moves the hexapod legs accordingly. We want to control the hexapod so that one top plate remains “flat” while the other is in motion. Ultimately, this system would be low-cost as compared to current stabilization systems.

This system has been named "**Instrument Geolocation and Pointing Stabilization System**" or **IGPSS**. NASA awarded us a grant to conduct a feasibility study of this concept.

## 3. Objective

The objective of this feasibility study is to take existing, relatively low cost technology available from NASA and see if a working model (the IGPSS) could be built. The primary components are the hexapod, the INS device and internal control circuitry. In this application, the INS supercedes the C-MIGITS II - a combination GPS/INS device originally used as a navigation system for Cruise Missiles.

A fully operational IGPSS will stabilize an instrument (such as a camera or spectrometer attached to one of the hexapod plates) against the motions of a light aircraft (the other plate) and provide absolute pointing knowledge and control. That is, the camera's position attached to the hexapod is independent of the position of the airplane, (within limits), and constant relative to the earth. This project's goal is to demonstrate that the data acquired by the stabilized instrument is of higher quality that from non-stabilized system and that the low cost of the IGPSS would open up other viabilities. Not only would a low cost IGPSS become available for commercial applications such as a local environmental resource for management, but also for use in military applications such as unmanned aerospace vehicles (UAVs).

As now configured in this application, the INS and GPS are unrelated separate devices, the first insures flatness or stability, and the second gives us location. Our simulation tests proved feasible when we used a stand-alone INS device to control the hexapod, rather than a combination GPS/INS such as in the CMIGITS.

## 4. Internal Control Circuitry

We have replaced an originally supplied Flexmotion Board with H-bridges that are high power control circuits to turn the actuators on and off. The actuators we used in this project were supplied by NASA; refer to www.ultramotion.com to see the specific device. The Flexmotion Board was originally incorporated to physically control the motion of the 6 (six) hexapod legs; however we found an alternative approach that we believe is superior. We found the H-Bridge provided better control. An initial calculation that defines the speed of response has been done. The current actuator moves at 2 inches per second (max) at 28 VDC. This amounts to 2 milli-inches per milli-second. We are assuming a total processing/conversion time of about 30 milli-seconds worst case for all 6 channels.

### *4.1. H-Bridge Hardware*

This H-bridge was implemented by using heavy-duty (5 amps) electromechanical relays with surge absorbing diodes.

Enhancements are envisioned for this H-bridge configuration by substituting the electromechanical relays with heavy duty MOSFETS. The control commands for the movement of the motor were implemented with LabView. The program calculated the amount of movement for each leg of the hexapod and moved the actuator in the appropriate direction. A feedback mechanism from each leg of the hexapod indicated the exact position of the actuator and the program terminated movement when each leg attained its correct position.

The H-BRIDGE for the hexapod can be used in the following ways.

**A) Forward or Reverse**

The Hexapod motion is implemented with six linear actuators. Each actuator is driven forward or reverse by an H-bridge configured circuit.

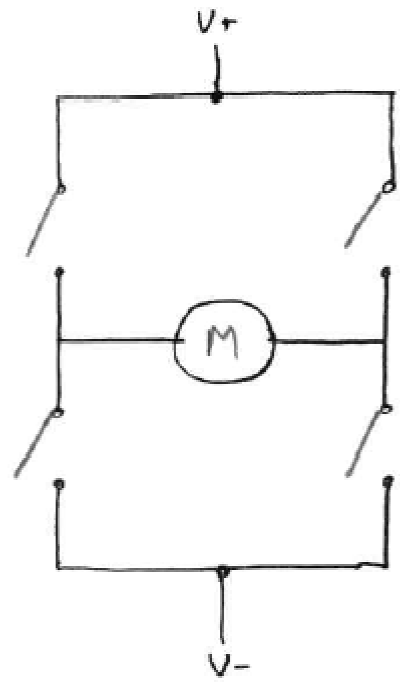



Figure 1 – H-Bridge Configured Circuit

The diagram shown above represents the H-bridge in it's resting or OFF state. All 4 relays are open and no power is applied to the motor which is in a stopped state.

**B) Forward Linear-Motor Movement State**

The diagram below represents the H-bridge in its forward linear-motor movement state. The two closed relays apply power to the motor with a positive polarity to result in forward motion.

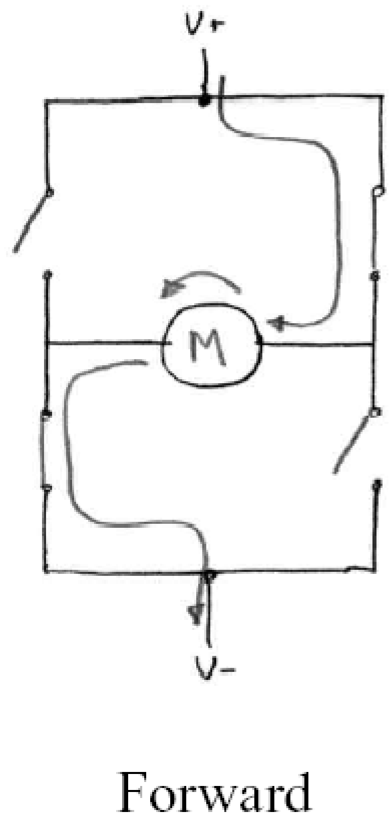
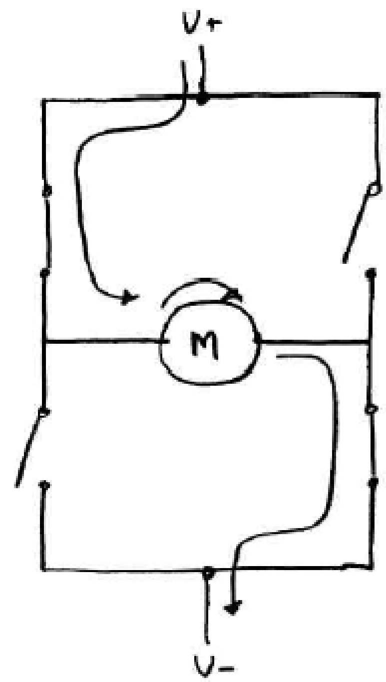



Figure 2 – H-Bridge Configured Circuit: Forward Linear-Motor Movement State

**C) Reverse Linear-Motor Movement State**

The diagram below represents the H-bridge in its reverse linear-motor movement state. The two closed relays apply power to the motor with a negative polarity to result in a reverse motion.




Reverse

Figure 3 – H-Bridge Configured Circuit: Forward Linear-Motor Movement State

## *4.2. H-Bridge Software*

We wrote four programs to operate the H- Bridge. These programs were developed using National Instruments LabView. The programs are listed below:

- H Bridge Microstrain Nulling.llb
- H Bridge All Manual Move.vi
- H Bridge One Manual Move.vi
- H Bridge Pattern Test With Excel.vi

These programs are included on the CD given to John Bolton. See **Appendix A** for Instructions to Use the H-Bridge hardware and software.

**A) H Bridge Microstrain Nulling Program**
This program allows you to move the hexapod in conjunction with the Microstrain INS device. (See Section 5 for detail about the INS). Perform the following steps in order to demonstrate the capabilities of the Hexapod and the Microstrain device; see Figure 1- H-Bridge MicroStain Nulling Front Panel.

**B) H Bridge All Manual Move**

This program is used to move all the six actuators at one time. All you have to do is specify the six voltages for the target value and hit the RUN arrow button once. The program will move the six actuators of the hexapod to the specified voltage with in the Tolerance levels. You can use the Tolerance control to determine the sensitivity and resolution of each move that is performed; see Figure 2 – H Bridge All Manual Move _ Front Panel.

**C) H Bridge One Manual Move.vi**

This program is used to perform moves on a single actuator at a time. Each actuator has its own Direction (Forward/Backward) and Start/Stop controls. Once the program is opened, you can hit on the RUN arrow button to run the program. The center Stop/Start button is used to quit the program; see Figure 3 – H Bridge One Manual Move Front Panel.

**D) H Bridge Pattern Test with Excel.vi**

This program was designed to move the hexapod to various positions and record the angles obtained from the micro strain device. The program creates an EXCEL spreadsheet which contains the Angles, Voltages, and Lengths of the hexapod at various positions. This program has the capability of running multiple cycles, up to a maximum of 4 cycles. Each cycle creates its own Excel spreadsheet, all under the same folder. You can change the start point, endpoint and the increments of each cycle. In this way the repeatability and resolution of the INS can be determined; see Figure 4 – H Bridge Pattern Test with Excel Front Panel.

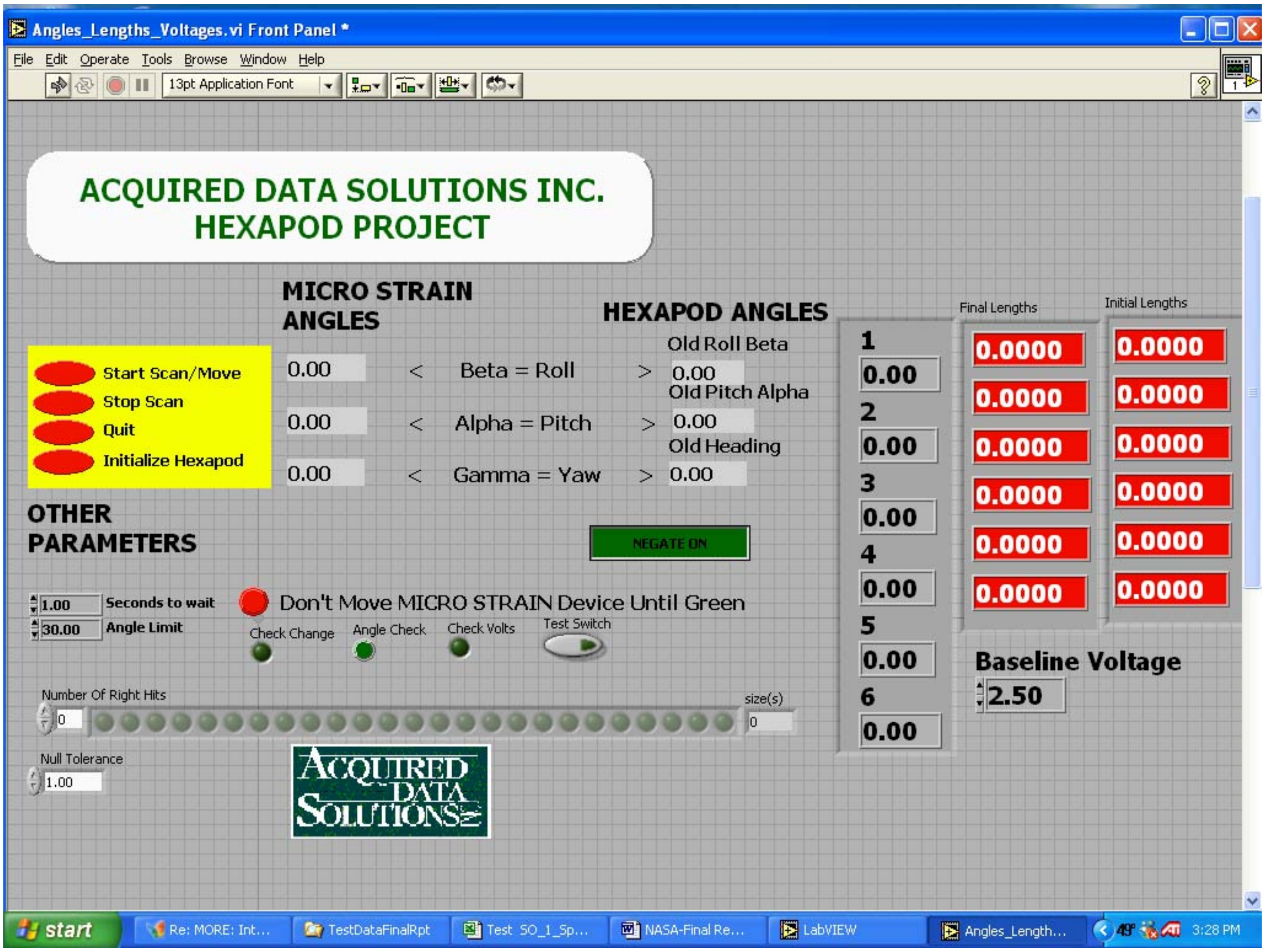

Angles_Lengths_Voltages.vi Front Panel *
File Edit Operate Tools Browse Window Help
13pt Application Font
ACQUIRED DATA SOLUTIONS INC.
HEXAPOD PROJECT
MICRO STRAIN ANGLES
HEXAPOD ANGLES
Final Lengths
Initial Lengths
Start Scan/Move
Stop Scan
Quit
Initialize Hexapod
Old Roll Beta
Beta = Roll
Old Pitch Alpha
Alpha = Pitch
Old Heading
Gamma = Yaw
OTHER PARAMETERS
NEGATE ON
Seconds to wait
Angle Limit
Don't Move MICRO STRAIN Device Until Green
Check Change
Angle Check
Check Volts
Test Switch
Number Of Right Hits
size(s)
Null Tolerance
Baseline Voltage
2.50
ACQUIRED DATA SOLUTIONS
start
3:28 PM

Figure 1

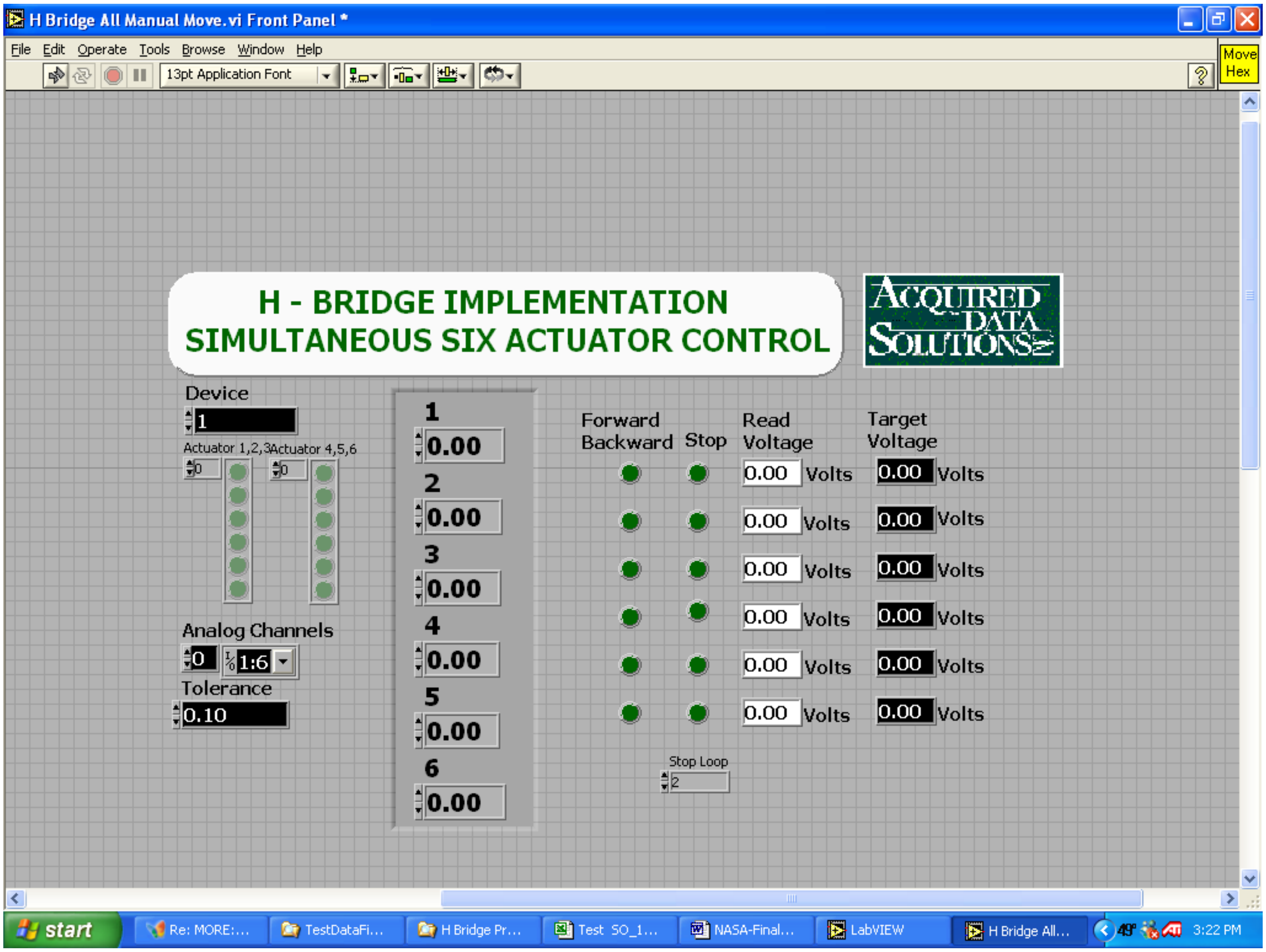

H Bridge All Manual Move.vi Front Panel *
File Edit Operate Tools Browse Window Help
13pt Application Font
Move
Hex
H - BRIDGE IMPLEMENTATION
SIMULTANEOUS SIX ACTUATOR CONTROL
ACQUIRED DATA SOLUTIONS
Device
1
Actuator 1,2,3
Actuator 4,5,6
Analog Channels
0
1:6
Tolerance
0.10
1
2
3
4
5
6
0.00
Forward Backward
Stop
Read Voltage
Target Voltage
Volts
Stop Loop
2
start
Re: MORE:...
TestDataFi...
H Bridge Pr...
Test SO_1...
NASA-Final...
LabVIEW
H Bridge All...
3:22 PM

Figure 2

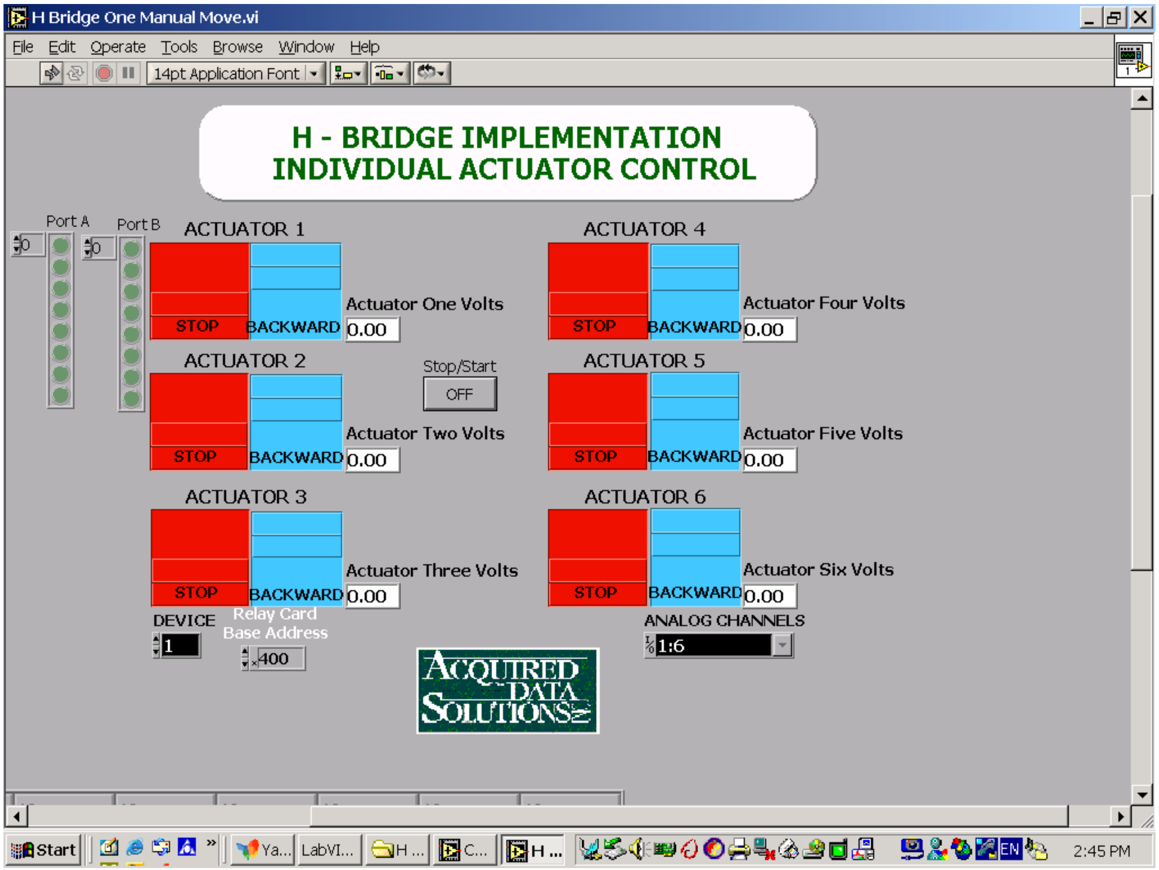



Figure 3 – H Bridge One Manual Move Front Panel.

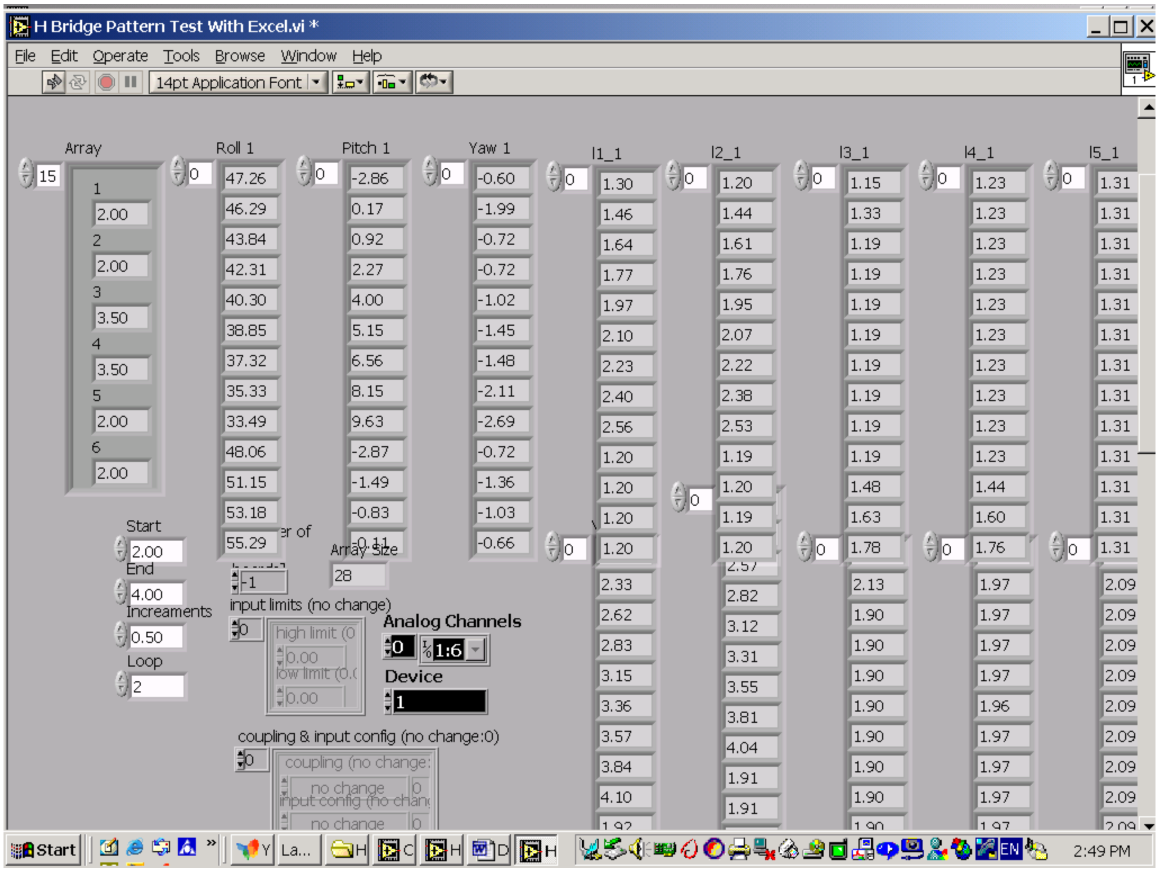

H Bridge Pattern Test With Excel.vi *
File Edit Operate Tools Browse Window Help
14pt Application Font
Array
Roll 1
Pitch 1
Yaw 1
I1_1
I2_1
I3_1
I4_1
I5_1
Start
End
Increaments
Loop
Array Size
input limits (no change)
Analog Channels
Device
coupling & input config (no change:0)
Start
2:49 PM

Figure 4

## 5. INS and the Hexapod

The INS device provides spatial orientation. Its outputs are signals that correspond to the three (3) inertial angles commonly referred to as pitch, roll and yaw. The mathematics converts these rotational signals into proportional linear motion for the six legs of the hexapod (see Phase II Report). A significant amount of software has been written for the hexapod - INS combination.

By getting 3 solid inertial angles, we are able to control the hexapod. Three internal interacting devices define these angles: the accelerometer, gyroscope and magnetometer. Our mission is to maintain "flat" position independent of vehicular motion. We initialize the hexapod by defining flat as that position where all six legs of the hexapod are equal and the top plate is measured with some reasonable tool such as a carpenter's level. Flat, in terms of the INS, can be initialized in terms of a reasonable tool. These INS angles would be 0,0,0 degrees by definition, and are correlated with the hexapod angles. (Radians or milli- radians are alternative units that may be more suitable for certain imaging devices, as suggested). A problem with the current implementation is that the hexapod cannot be commanded to return to its original position. Analysis suggests that this problem is correctable in the mathematics

### *5.1. Position Repeatability (3D-MG and Hexapod)*

Position repeatability means to be able to start the hexapod in a certain position, and then to be able to return to that original position. We were not able to accomplish this when the INS is controlling the six hexapod lengths. However, we were able to show that the INS is very repeatable when it is placed in various positions with the hexapod using this program (H Bridge Pattern Test With Excel.vi). Our suspicions are that this may result from incomplete mathematics.

Refer to the modified e-mail below sent from Louis Seiden to John Bolton on why we were concentrating efforts on the INS device from MicroStrain.

----- Original Message -----
**From:** louis seiden
**To:** john.bolton@gsfc.nasa.gov
**Sent:** Monday, August 26, 2002 3:47 PM
**Subject:** HEXAPOD/INS 26AUG02

[Modified – e-mail; see E-mail **1, Appendix B** for actual e-mail]

*We are now concentrating our efforts on the 3DM-G from Microstrain. This device is very new and it appears that it is a true INS device where we can get three independent angles (pitch, roll, yaw) straight up, without resorting to packing the Hexapod into a van to get motion for the 3rd angle (true heading for the C-Migits). The 3DM-G allows us to view INS and GPS as independent entities, which I believe was the original thought about this project. The 3DM-G has three interacting units: gyroscope, accelerometer, magnetometer. These three devices interact in some proprietary manner and optimum* *manner for some applications. However, the signals can be captured independently if desired. The gyroscope yields high frequency signals, while both the accelerometer and magnetometer yield low frequency signals.*

*The reference coordinate system is tied to the earth. Various filters are available so that weighing of the three devices can be changed (error tracking gain, bias tracking gain).*

*The manuals are still being developed, so for the time being we will be working with individual conversations and correspondences. The magnetometer is not present in the C-Migits; this will basically allow us to get the third INS angle without motion. Of course magnetic material cannot be in the local vicinity of the 3DG-D.*

*Looking at this in sequence or frame by frame, after some force picks up the nose of the airplane, the imaging device is no longer parallel to the ground as you say. We know this because the INS reading has changed-it is no longer (49, 0, 0) which we define as "flat", null position or parallel to the ground. We wish the imaging device to return to (49, 0, 0) and the only way we can do this is by adjusting the actuator lengths.*

*We have decided to go back to the "manual" program where we can control the actuator lengths. The math gets us to lengths (19, 19, 19, 19, 19, 19) or in the virtual case three axes of equal length where 19 is a hypotenuse of a right triangle.*

*The "manual-sequence" case will allow us to read the INS in several different positions numerous times to show repeatability of the INS angles. It will also allow us to return to "flat" or null so we can make a comparison with the math, and perhaps find an approximate scaling factor.*

## *5.2. Experiment*

This experiment is based upon the fourth Hexapod program (H Bridge Pattern Test with Excel.vi) that allows all of the hexapod legs to start out with the same lengths, and after a series of incremental moves, return to their original positions.

The experiment showed that the hexapod can be positioned accurately and that the angles that the INS generates are repeatable; see Spreadsheet 1. Five additional runs are shown in Appendix C.

Each spread sheet shows the Roll, Pitch and Yaw input into the software program (H Bridge Pattern Test with Excel.vi), as well as the six (6) voltages and six (6)actuator lengths. See Appendix B for the spreadsheet results of the (6) tests that were run.

| | V=Voltage; A=Actuator; L=Length | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | |
| ROLL | PITCH | YAW | V1 | V2 | V3 | V4 | V5 | V6 | L_A1 | L_A2 | L_A3 | L_A4 | L_A5 | L_A6 |
| 48.496 | 2.665 | -83.811 | 1.245 | 1.248 | 1.279 | 1.239 | 1.242 | 1.245 | 1.992 | 1.997 | 2.046 | 1.982 | 1.987 | 1.992 |
| 45.698 | -0.385 | -83.726 | 1.556 | 1.544 | 1.279 | 1.239 | 1.242 | 1.245 | 2.49 | 2.471 | 2.046 | 1.982 | 1.987 | 1.992 |
| 42.64 | -3.519 | -83.44 | 1.862 | 1.865 | 1.279 | 1.239 | 1.242 | 1.248 | 2.979 | 2.983 | 2.046 | 1.982 | 1.987 | 1.997 |
| 39.529 | -6.895 | -83.151 | 2.179 | 2.173 | 1.279 | 1.239 | 1.242 | 1.245 | 3.486 | 3.477 | 2.046 | 1.982 | 1.987 | 1.992 |
| 36.116 | -10.296 | -82.641 | 2.487 | 2.499 | 1.279 | 1.239 | 1.242 | 1.245 | 3.979 | 3.999 | 2.046 | 1.982 | 1.987 | 1.992 |
| 48.293 | 2.574 | -83.895 | 1.251 | 1.26 | 1.279 | 1.239 | 1.242 | 1.245 | 2.002 | 2.017 | 2.046 | 1.982 | 1.987 | 1.992 |
| 47.367 | 6.411 | -83.331 | 1.251 | 1.26 | 1.55 | 1.547 | 1.245 | 1.245 | 2.002 | 2.017 | 2.48 | 2.476 | 1.992 | 1.992 |
| 45.904 | 10.618 | -83.266 | 1.251 | 1.257 | 1.865 | 1.865 | 1.242 | 1.245 | 2.002 | 2.012 | 2.983 | 2.983 | 1.987 | 1.992 |
| 44.454 | 14.811 | -83.42 | 1.251 | 1.257 | 2.173 | 2.176 | 1.242 | 1.245 | 2.002 | 2.012 | 3.477 | 3.481 | 1.987 | 1.992 |
| 42.761 | 19.207 | -83.915 | 1.251 | 1.257 | 2.487 | 2.487 | 1.242 | 1.245 | 2.002 | 2.012 | 3.979 | 3.979 | 1.987 | 1.992 |
| 48.566 | 2.589 | -83.203 | 1.251 | 1.257 | 1.248 | 1.251 | 1.242 | 1.245 | 2.002 | 2.012 | 1.997 | 2.002 | 1.987 | 1.992 |
| 52.696 | 1.72 | -83.376 | 1.254 | 1.26 | 1.248 | 1.251 | 1.547 | 1.544 | 2.007 | 2.017 | 1.997 | 2.002 | 2.476 | 2.471 |
| 57.262 | 0.755 | -83.598 | 1.251 | 1.257 | 1.245 | 1.251 | 1.862 | 1.855 | 2.002 | 2.012 | 1.992 | 2.002 | 2.979 | 2.969 |
| 61.824 | -0.399 | -83.729 | 1.254 | 1.257 | 1.248 | 1.251 | 2.17 | 2.167 | 2.007 | 2.012 | 1.997 | 2.002 | 3.472 | 3.467 |
| 66.537 | -1.476 | -84.021 | 1.251 | 1.257 | 1.248 | 1.251 | 2.484 | 2.484 | 2.002 | 2.012 | 1.997 | 2.002 | 3.975 | 3.975 |
| 48.923 | 2.449 | -83.497 | 1.251 | 1.26 | 1.248 | 1.251 | 1.257 | 1.257 | 2.002 | 2.017 | 1.997 | 2.002 | 2.012 | 2.012 |
| | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |

**Spreadsheet 1 - Evaluation of INS, Based Repeated Hexapod Positions (Test SO_1)**

Refer to the modified e-mail below sent from Louis Seiden to Alex Martin provides a summary of the experiment.

> ----- Original Message -----
> **From:** Louis Seiden
> **To:** amartens@ctc.org
> **Cc:** John Bolton
> **Sent:** Thursday, January 30, 2003 4:02 PM
> **Subject:** Hexapod Information and Data 30Jan03
>
> [Modified – e-mail; see E-mail **2, Appendix B** for actual e-mail]
>
> *The 3-dimemtional INS device (gyroscope, accelerometer, and magnetometer) can measure a stationary position as well as dynamic motion.) Although, interacting local magnetic fields could pose a problem, we have been told by David Churchill (Microstrain) and believe this will not be a problem in an airplane.*
>
> *We have recently reworked the system with H-bridge relays and variable control over the speed of the actuators. The voltage resolution associated with the actuators is about 0.02 volts (8 inches of actuator motion are represented by 5 volts - ideally we would like to have actuators where .8 inches yield 5 volts).*
>
> *Some reprehensive data is attached, which shows that the INS device is repeatable to better than +/- 0.2 degrees. Some of that error is due to our ability to exactly reposition the 6 actuator lengths, hence adding to the INS error. Here is a test set of data. Additional tests are in the appendix. The actuators lengths (all six) start out at the same length and are incremented to 16 different positions, the last being the same as the first (as close as possible) [See Spreadsheet #1]*
> *We have been told that better INS devices are being developed. Also, now that we have better control of the hexapod, we will take a proper look at the mathematics which allows us to convert the 3 inertial angles to 6 actuator lengths with 3 measured angles in the stationary mode. We have probably taken this project as far as we can, without some commercial partners or some other type of funding. Any suggestions that you may have will certainly be appreciate*

### *5.3. **INS Device -** 3DM-G User Manual*

See Appendix _ for Current 3DM-G User Manual or download it from www.microstrain.com

## 6. Math Issues

These several emails reflect the dilemma. For example we do not believe a 4 x 4 matrix is necessary, which is the opinion of at least one other expert. The mathematical analysis is beyond our in house expertise.

Refer to the modified e-mail below sent from Louis Seiden to John Bolton on October 9, 2002 about difficulty to revert the hexapod back to its original position based upon the INS readings. These reading were translated by the mathematics into hexapod six (6) leg lengths.

[Modified – e-mail; see E-mail **#3, Appendix B** for actual e-mail]

----- Original Message -----
**From:** louis seiden
**To:** john.bolton@gsfc.nasa.gov
**Cc:** Lseiden@LSEplus.com ; SAMbutz@LSEplus.com ; STEVE.seiden@acquiredata.com ; yusuf.chitalwala@acquiredata.com
**Sent:** Wednesday, October 09, 2002 7:19 PM
**Subject:** Pointing the hexapod 09OCT02

*We have had difficulty pointing in the right direction using the math that was developed for the hexapod. Both the pointing laser and the 3DM-G /INS device are sitting on the top plate of the hexapod. The INS device and the actuator lengths ( 8 inches=5volts) do not seem to react properly when we try a closed solution.*

*We decided to test the repeatability of the INS as a possible source of this difficulty by building an experimental spreadsheet (table). you will find attached a small table, although the program can generate as many points as we choose. This is our first table. The first point in the table is defined as "flat", null or parallel to the earth.*

*The object is to always return the top or camera plate to its "flat" position. We are in the process of studying the table that we generated today. It was generated by moving the hexapod to numerous positions and recording the INS angles. The reverse process is to find the INS angles in the chart, compare the voltage points of the six actuators with the voltage points that define "flat", and return the camera or top plate to the "flat" position.*

*Also, we will generate each table several times to get a better feeling for the repeatability of the INS angles. In addition, when we feel comfortable with this approach, we will ask Charlie to see if we can correlate this data with the math solution.*

*Note: We could not try this with the C-MIGITS because we never had 3 solid INS angles to work with (the acceleration problem).*

See Email 4, Appendix B, for John Bolton's response to the above e-mail.

Refer to the modified e-mail below sent to Charlis Nguyan from Louis Seiden about mathematics.

[Modified – e-mail; see e-mail **#5, Appendix B** for actual e-mail]

----- Original Message -----

**From:** louis seiden
**To:** nguyen@pluto.ee.cua.edu
**Cc:** bod@acquiredata.com ; louis.seiden@acquiredata.com
**Sent:** Wednesday, April 09, 2003 4:18 PM
**Subject:** Re: Hexapod Math Meeting 3Apr03

*I have a few thoughts and I would like your comments. It seems to be that at least one of our short coming in the INS/hexapod project is the mathematics. Obviously, if we are to get to the 'hexapod flat table' system right, we need the proper equations and the only way we can get them is to work with you. But we were working on a very limited feasibility grant which has been spent, and unfortunately we spent much of our time using the C-MIGITS II (cruise missile component) which turned out not to be suitable. The C-MIGITS II depends on GPS and uses INS only incidentally- for example when GPS coordinates are blocked from view. As far as I can tell the partial INS is used for short periods of time, when for example the missile is in valleys or behind tall buildings.*

*As we discussed, finding a commercial partner is vital. We have no way of knowing if the math problem is the only problem, or the level of programming difficulty in going from a 3 x 3 matrix to a 4 x 4 matrix. As you pointed out this is a robotics problem; we want a smooth transition as the airplane yaws, pitches and rolls, so that the 'hexapod flat table' appears to always be flat without intermediate vibration. This does not all need to be done at once, but we need some commercial support, and a pretty good 'feasibility' road map.*

*You asked me what I think. I don't want you to work for free, nor can I afford to get ADS involved in an open ended, research project without customers, or a commercial partner. As Dean of the Engineering Department, I know even if you wished to spend more time on this project it is generally not available. From our point of view, even if we can create the 'flat hexapod table' in the stationary state, we have to show that the 'flat hexapod table' condition holds when the whole system is in motion (van, airplane etc.) It seems to me that taking things in the proper order and not walking away completely from our software and electronics effort.*

1. *I should write the final feasibility status report indicating that additional math solutions are available but not in our possession.*
2. *Talk to John Bolton and Alex Martens ( the NASA associate tasked with finding commercial partners (585-218-4260)) about creating a phase iv that deals with completing the mathematics and reducing it to software.*
3. *Possibility use the large Catholic University hexapod as a precise positioning device for our smaller hexapod/INS combination.*
4. *Talk to David Churchill at MicroStrain and others, if they exist, about high quality INS devices.*

*It is quit clear to me that continuing only makes sense with colleagues and commercial partners and /or customers. For us to make money we have to make sure that there is still an interest in this environmental project, so we can provide a complete package if we choose. I would prefer to pursue this path and would like to get your thoughts and those of others at ADS.*

# 7. Going Forward

## *7.1. Enhancements to the Current H-Bridge Configuration*

To speed up and enhance the positioning and control mechanisms and software for the H-Bridge the following are recommended:

(1) Replace the current linear actuators with actuators that have smaller total linear movement but higher movement resolution. Currently the linear actuator is moving 1 inch per volt and finer control can be realized if it moves 1 inch per 24 volts. Since we are adjusting for very small attitude adjustments for the hexapod platform we do not need very large arm movements and we also need finer control of these movements.

(2) Replace the slow electromechanical relays in the H-Bridge with solid-state, high current MOSFET switches that can absorb the surges and inductive kicks of the linear actuator motors. International Rectifier is manufacturing complete H-Bridge units with height current and high surge capabilities that can be used for this purpose.

(3) Offload the control software from the main computer software (currently LabView) to firmware based microcontrollers for each arm of the Hexapod.

This enhancement will add controller hardware & firmware for each arm of the Hexapod. The LabView control program residing on the main PC will issue positioning commands to each of the 6 microcontrollers over a daisy chain or ring type of bus (either USB or RS-485). Each microcontroller will then will execute the positioning sequence algorithm to move its corresponding arm to the required position to realize the correct platform attitude.

This is a much better arrangement since it relieves the PC (Labveiw) program from the mundane details of position control and hands it over to a firmware based solution that will improve the speed of response by at least two orders of magnitude.

## *7.2. Alternative to the Hexapod*

Refer to the modified e-mail below sent to John Bolton from Louis Seiden.

[Modified – e-mail; see e-mail **#6, Appendix B** for actual e-mail]

**From:** louis seiden
**To:** john.bolton@gsfc.nasa.gov
**Cc:** SAMbutz@LSEplus.com ; STEVE.seiden@acquiredata.com ; yusuf.chitalwala@acquiredata.com
**Sent:** Saturday, November 09, 2002 10:52 AM
**Subject:** NASA going forward 09Nov02

(NASA going forward 09Nov02)
*I want to follow up on our last phone conversation about a week or so ago. We talked about the possibilities of blending together some of the expertise and experiences of several groups. We talked about Microstrain (3DMG)and their interest in developing the next level of INS devices around gyroscopes, accelerometers and magnetometers and the Analog Devices program for MEMS gyroscopes. You mentioned a group in Rochester that was working with a Canadian INS device that was more expensive than 3DMG. Also, we talked about linearity, sensitivity, inertia, pulse widths and resolution.*

*We wanted to do a few more experiments, which basically involved revisiting the Flexmotion board with the 3DMG INS device. We did those experiments and talked to NI. Our conclusions were that we could not do as well with the Flexmotion board. We are currently using software and hardware that we either developed or integrated.*

*Yesterday, we met with Mark Wood (508-832-3456), senior sales engineer at Polytec PI, which is located in Auburn, MA. Mark was in the Rockville area for NI days-Steven met him and pointed him in my direction. The PI stands for Physik Insrumente, the German micro-positioning, nano-positioning and automation company, with which we are both familiar. They specialize in hexapods and and alternative positioning devices. Also they tell me that they are very involved with NASA in the next generation space telescope (Webb telescope scheduled for launch around 2008 to 2010). Their least expensive hexapod, with software and a controller is more than $50K. This device supports about 45 pounds and can resolve 3 microns. Since part of our mission and objective is to find a relatively inexpensive and feasible solution, we looked at alternatives. I understand that the PI catalog is on-line at:*

> *www.pi.ws*
>
> *We reviewed a possible solution under $15K that, we believe, has sufficient range and can support about 10 pounds. I don't know the weight of your camera. Their solution is called rotation, tip and tilt, which could be called roll, pitch and yaw. This solution would involve, a rotation stage (7-60 and 7-61 of the catalog) and a tip/tilt stage (7-63).*

*We are also in the process of putting together a comprehensive report based upon this memo and our studies. We wanted you to know our thoughts at this point. As you pointed, out the hard part is to determine the direction from here. We obviously need your help with that.*

# 8. Conclusions

## *8.1. Project Conclusions*

We have defined several areas for development that need to be resolved. Although, the 3-deminsional INS device that we were using seems to be quite reliable, improved versions may now be available. The H-bridge system of relay devices should be pursues using high-powered solid-state services. We believe that the mathematics needs to be reviewed for completeness and errors. In addition, the advantage of spherical coordinates needs to be explored. Further, we believe that the speed and flexibility of the system will be enhanced by individual processors on each hexapod leg with actuators that are capable of greater speed and acceleration.

Finally, we still believe that this process is feasible. The proposed tip table solutions (by PI) may be a practical alternative in terms of cost and performance.

## 8.2. *Market Potential*

Space stabilization through a hexapod is not a breakthrough; many sensors are currently pointed/stabilized with this technology. However, there does appear to a significant market for a low cost device. The current market is primarily military, but cost of those devices (specified to work in very hostile environments) drives many potential civilian users from the market. A lower cost device could open this market. There are many applications for the stable platform, including all those that are currently served by simpler instrument stabilization systems. The primary application, however, is in the pointing and the quality of the data must be improved and the data accurately located (geo-located).

The potential size of the market is very large; the IGPSS could be used with any type of imaging system. It can be built to virtually any size using the same basic principles. Such scalability makes it very versatile. Instruments (i.e., camera, spectrometers) of any size can be mounted. The technology impact is very large because the quality of the raw data collected by the instrument would be greatly improved, and significantly reduce the amount of post-process imaging needed to resample and geo-locate data.

The primary application, which we had hoped to test in partnership with industry, is the stabilization of a push broom imaging spectrometer. Much experience has been gained in the use of this imaging spectrometer system, and its associated systems operating in the non-stabilized mode. This step has not been reached yet.

The primary societal impact is that this system could make available higher quality, geo-located imaging data at significantly lower ownership costs. This would have a particular significant impact on the price and turn around time for the data acquired from the airborne platform.

## Appendix A: H-Bridge Instructions

### *1. Hardware Setup*

1) Place the Microstrain device on top of the Hexapod platform. Also place the Laser light next to the Microstrain device.

2) Turn the blue Sensor Box ON.

3) Turn the big Power Supply box ON.

4) Once you have completed the above steps, you are now ready to run the program.

## *2. Software Setup*

1) Open the H Bridge Microstrain Nulling program, located in the path mentioned above.

2) Once you have opened the program, hit the RUN arrow button.

3) There are 6 main buttons that you should be aware off, namely Start Scan/Move, Stop Scan, Quit, Initialize Hexapod, Negate ON/OFF, and Test Switch.

4) Test Switch: This button is used to either move (TRUE) or NOT move (FALSE) the hexapod in conjunction with the Microstrain INS. Make sure this switch is appropriately turned off or on, before you hit the Start Scan/Move button.

5) Start Scan/Move: This button is used to start the scanning of new angles from the Microstrain INS and move the hexapod to the new positions calculated from the new angles.

6) Stop Scan: This button stops the scanning process.

7) Quit: This button stops the program completely. Therefore you would have to hit the RUN arrow key to run the program again.

8) Initialize Hexapod: This button is used to initialize the Hexapod to a flat position, by internally sending all 2.5 volts to all the six actuators.

9) Negate ON/OFF: This button is primarily used to compare the functional differences between either adding or subtracting the difference between the old and new angles obtained from the Microstrain INS.

10) Test Switch: This button is used to perform move, prior to hitting Start Scan/Move button.

11) There are other sensitivity parameters that you can be used to improve the response of the hexapod to the Microstrain INS. They are “Seconds to wait” after a move is performed, and “Angle Limit” to limit the motion.

# Appendix B: Emails

## Email 1

----- Original Message -----
**From:** John Bolton
**To:** louis seiden
**Sent:** Monday, August 26, 2002 3:21 PM
**Subject:** Re: Hexapod/INS 26AUG02

Greetings Lou,

Thanks for the update. I got your phone message and have been intending to call, but got hung up today.

It sounds like this new gizmo is pretty promising. How are you going to get GPS information if you use only the 3DM-G? Have you had a chance to really compare the performance of the Microstrain gadget vs. the C-Migits? One thing that I am concerned about is the long-term stability. Relying on the magnetometer as a replacement for INS motion might be a bit tricky.

Let me know when you have a bit better results so you can compare the performance of the devices. At least it is relatively cheap.

See you,

John

At 03:47 PM 8/26/2002 -0400, you wrote:

Hello John,
26Aug02

We are now concentrating our efforts on the 3DM-G from Microstrain. This device is very new and it appears that it is a true INS device where we can get three independent angles (pitch, roll, yaw) straight up, without resorting to packing the Hexapod into a van to get motion for the 3rd angle (true heading for the C-Migits). The 3DM-G allows us to view INS and GPS as independent entities, which I believe was the original thought about this project. Hopefully we can go directly from the laboratory to the sky.

The original application is in bio-mechanics for people who had become paralyzed to one extent or another and were trying to regain some form of motion. The 3DM-G has three interacting units: gyroscope, accelerometer, magnetometer. These three devices interact in some proprietary manner and optimum manner for some application. However, the signals can be captured independently if desired. The gyroscope yields high frequency signals, while both the accelerometer and

magnetometer yield low frequency signals.
The reference coordinate system is tied to the earth. Various filters are available so that weighing of the three devices can be changed (error tracking gain, bias tracking gain).

The manuals are still being developed, so for the time being we will be working with individual conversations and correspondences. The magnetometer is not present in the C-Migits; this will basically allow us to get the third INS angle without motion. Of course magnetic material cannot be in the local vicinity of the 3DG-D. Today, I expect to get the trigonometry ideas to convert their data streams to three INS angles. An added plus is that in their previous work, they have had some experience with hexapods and want to work with us..

Thanks,
Lou

John Bolton Technology Development
EOS-Goddard Program Office
Code 420 NASA/Goddard Space Flight Center
Greenbelt, MD 20771 U.S.A.
personal telephone: (301) 286-8547
secretary telephone: (301) 286-9694 (Debbie Hamby)
office telefax: (301) 286-1145
e-mail: john.bolton@gsfc.nasa.gov
web: http://carstad.gsfc.nasa.gov

## Email 2

----- Original Message -----
**From:** Louis Seiden
**To:** amartens@ctc.org
**Cc:** John Bolton
**Sent:** Thursday, January 30, 2003 4:02 PM
**Subject:** Hexapod Information and Data 30Jan03

Hello Alex,

The picture in your introductory letter is somewhat dated, since it shows a combination GPS/INS device. We are now using a 3-dimemtional INS device (gyroscope, accelerometer, magnetometer) that can measure stationary as well as dynamic motion. There are correspondences between John and I about this change, which has cost benefits as well as practical benefits. Although, interacting local magnetic fields could pose a problem, we have been told and believe this will not be a problem in an airplane.

We have recently reworked the system with H-bridge relays and variable control over the speed of the actuators. The voltage resolution associated with the actuators is about 0.02 volts (8 inches of actuator motion are represented by 5 volts - ideally we would like to have actuators where .8 inches yield 5 volts).

Some representive data is attached, which shows that the INS device is repeitable to better than +/- 0.2 degrees. Some of that error is due to our ability to exactactly reposition the 6 actuator lengths, hence adding to the INS error.

We know that better INS devices are being developed. Also, now that we have better contol of the hexapod, we will take another look at the mathematics which allows us to convert the 3 inertial angles to 6 actuator lengths. We have probably taken this project as far as we can, without some commercial partners or some other type of funding. Any suggestions that you may have will certainly be appreciate.

Louis Seiden

Director of Technology
Acquired Data Solutions, Inc.
1225 Martha Custis Drive
Unit C-1
Alexandria, VA 22302

Work: 703-379-5303 Ext. 22
Home office: 301-468-5928

## Email 3

----- Original Message -----
**From:** louis seiden
**To:** john.bolton@gsfc.nasa.gov
**Cc:** Lseiden@LSEplus.com ; SAMbutz@LSEplus.com ; STEVE.seiden@acquiredata.com ; yusuf.chitalwala@acquiredata.com
**Sent:** Wednesday, October 09, 2002 7:19 PM
**Subject:** Pointing the hexapot 09OCT02

Hi John 09Oct02,

We have had difficulty pointing in the right direction using the math that was developed for the hexapod. Both the pointing laser and the 3DM-G /INS device are sitting on the top plate of the hexapod. The INS device and the actuator lengths ( 8 inches=5volts) do not seem to react properly when we try a closed solution.

We decided to handle this difficulty by building an experimental table. You will find attached a small table, although the program can generate as many points as we choose. This is our first table. The first point in the table is defined as "flat", null or parallel to the earth.

The object is to always return the top or camera plate to its "flat" position. We are in the process of studying the table that we generated today. It was generated by moving the hexapod to numerous positions and recording the INS angles. The reverse process is to find the INS angles in the chart, compare the voltage points of the six actuators with the voltage points that define "flat", and return the camera or top plate to the "flat" position.

Also, we will generate each table several times to get a better feeling for the repeatability of the INS angles. In addition, when we feel comfortable with this approach, we will ask Charlie to see if we can correlate this data with the math solution.

Note: We could not try this with the C-MIGITS because we never had 3 solid INS angles to work with (the acceleration problem). As always I will keep in touch.

Thanks,
Lou

Louis Seiden

## Email 4

From: John Bolton <john.bolton@gsfc.nasa.gov>
>To: "louis seiden" <lseiden@msn.com>
>CC: Lseiden@LSEplus.com, SAMbutz@LSEplus.com, STEVE.seiden@acquiredata.com,
> yusuf.chitalwala@acquiredata.com
>Subject: Re: Pointing the hexapot 09OCT02
>Date: Thu, 10 Oct 2002 09:41:32 -0400
>
>Greetings Lou,
>
>It looks like you are doing quite a lot of tedious work to try to figure
>out how the hexapod is working. One thing that occurs to me when looking
>at your table is that you do not have any Z-axis control. It will be
>necessary to assure that the vertical movement of the hexapod is
>controlled. What we really want, as we have discussed, is for the centroid
>of the top plate to move along the surface of an imaginary sphere with a
>radius equal to some nominal distance. Thiat distance should be something
>like the distance from the base to the top plate when the actuators are
>extended half way.
>
>I suppose you have already expended your budget, but maybe you can get
>Charlie or one of his associates to look into this. It might be a lot more
>efficient to get somebody who has already gone through this exercise,
>rather than to try to figure it out yourselves.
>
>I'll be away for the Columbus Day week. Let me know how things turn out.
>
>See you,
>
>John

## Email 5

----- Original Message -----
**From:** louis seiden
**To:** nguyen@pluto.ee.cua.edu
**Cc:** bod@acquiredata.com ; louis.seiden@acquiredata.com
**Sent:** Wednesday, April 09, 2003 4:18 PM
**Subject:** Re: Hexapod Math Meeting 3Apr03

Hi Charlie:

I have a few thoughts and I would like your comments. It seems to be that at least one of our short coming in the INS/hexapod project is the mathematics. Obviously, if we are to get to the 'hexapod flat table' system right, we need the proper equations and the only way we can get them is to work with you. But we were working on a very limited feasibility grant which has been spent, and unfortunately we spent much of our time using the C-MIGITS II (cruise missile component) which turned out not to be suitable. The C-MIGITS II depends on GPS and uses INS only incidentally- for example when GPS coordinates are blocked from view. As far as I can tell the partial INS is used for short periods of time, when for example the missile is in valleys or behind tall buildings.

As we discussed, finding a commercial partner is vital. We have no way of knowing if the math problem is the only problem, or the level of programming difficulty in going from a 3 x 3 matrix to a 4 x 4 matrix. As you pointed out this is a robotics problem; we want a smooth transition as the airplane yaws, pitches and rolls, so that the 'hexapod flat table' appears to always be flat without intermediate vibration. This does not all need to be done at once, but we need some commercial support, and a pretty good 'feasibility' roar map.

You asked me what I think. I don't want you to work for free, nor can I afford to get ADS involved in an open ended, research project without customers, or a commercial partner. As Dean of the Engineering Department, I know even if you wished to spend more time on this project it is generally not available. From our point of view, even if we can create the 'flat hexapod table' in the stationary state, we have to show that the 'flat hexapod table' condition holds when the whole system is in motion (van, airplane etc.)
It seems to me that taking things in the proper order and not walking away completely from our software and electronics effort.

1. I should write the final fesibility status report indicating that additional math solutions are available but not in our possession.
2. Talk to John Bolton and Alex Martons ( the NASA associate tasked with finding commercial partners (585-218-4260)) about creating a phase III that deals with completing the mathematics and reducing it to software.
3. Possibility use the large Catholic University hexapod as a precise positioning device for our smaller hexapod/INS combination.

4. Talk to David Churchill at MicroStrain and others, if they exist, about high quality INS devices.

It is quit clear to me that continuing only makes sense with colleagues and commercial partners and /or customers. For us to make money we have to make sure that there is still an interest in this environmental project, so we can provide a complete package if we choose. I would prefer to pursue this path and would like to get your thoughts and those of others at ADS.

Lou Seiden

>From: "Dr. Charles Nguyen" <nguyen@pluto.ee.cua.edu>
>To: louis seiden <lseiden@msn.com>
>Subject: Re: Hexapod Math Meeting 3Apr03
>Date: Tue, 8 Apr 2003 10:52:43 +0000 (UTC)
>
>
>Louis:
>I would like to help you but cannot continue to work for free. If you
>would like to get the mathematical solution of the problem, I can spend
>about 10 hours with $100/hour to prepare the material for you. Please let
>me know what you think.
>Thanks,
>Charlie
>
>
>
>On Thu, 3 Apr 2003, louis seiden wrote:
>
> > Hello Charlie,
> >
> >
> >
> > We wish to thank you again for the time that you found for us in your
>very tight schedule. In this very stressed time, there is an obvious
>emphasis on defense and homeland security. Since our project involves
>technology transfer and environmental studies, and we need to find a
>commercial partner, it seems to me that we have to at least have to know
>how to maintain a 'flat hexapod table' when the bottom plate is not
>attached to earth coordinates, as opposed to airplane coordinates.
> >
> > As I write a final report, I would like to include the proper matrix as
>a way to go to the next phase. Since this is apparently a well known
>solution, if you could point us in the right direction and the world
>improves a bit (which is possible), we may be able to find the ally that we
>need.
> >
> >
> > I believe that you told us that this is a robotics problem that that has
>been solved and that the 3x3 matrix that we are using and that includes
>inertial angles, needs to be expanded to a 4x4 matrix that includes x, y

>and z as well as a, b and g.
> >
> > Thank you,
> >
> > Lou Seiden
> >
> >
> >
>
>--
>+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+
>| Dr. Charles C. Nguyen, Ph.D.                    Phone: 202-319-5160 |
>| Dean, School of Engineering                                            |
>| Professor of Electrical Engineering           Fax:   202-319-4499 |
>| and Computer Science                                                 |
>| Catholic University of America          Email: nguyen@cua.edu |
>| Washington DC, 20064       |
>|              http://engineering.cua.edu/dean                       |
>+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+=+
>

## Email 6

----- Original Message -----

From: louis seiden
To: john.bolton@gsfc.nasa.gov
Cc: SAMbutz@LSEplus.com ; STEVE.seiden@acquiredata.com ; yusuf.chitalwala@acquiredata.com
Sent: Saturday, November 09, 2002 10:52 AM
Subject: NASA going forward 09Nov02

Hi John,

Please open this attachment. My ADS e-mail is very sick, so please send your notes to lseiden@msn.com and lseiden@acquiredata.com for now.

Thanks,
Lou

[The Attachment is below]

NASA going forward 09Nov02

Hi John,

I want to follow up on our last phone conversation about a week or so ago. We talked about the possibilities of blending together some of the expertise and experiences of several groups. We talked about Microstrain (3DMG)and their interest in developing the next level of INS devices around gyroscopes, accelerometers and magnetometers and the Analog Devices program for MEMS gyroscopes. You mentioned a group in Rochester that was working with a Canadian INS device that was more expensive than 3DMG. Also, we talked about linearity, sensitivity, inertia, pulse widths and resolution.

We wanted to do a few more experiments, which basically involved revisiting the Flexmotion board with the 3DMG INS device. We did those experiments and talked to NI. Our conclusions were that we could not do as well with the Flexmotion board. We are currently using software and hardware that we either developed or integrated.

Yesterday, we met with Mark Wood (508-832-3456), senior sales engineer at Polytec PI, which is located in Auburn, MA. Mark was in the Rockville area for NI days-Steven met him and pointed him in my direction. The PI stands for Physik Insrumente, the German micro-positioning, nano-positioning and automation company, with which we are both familiar. They specialize in hexapods and and alternative positioning devices. Also they tell me that they are very involved with NASA in the next generation space telescope (Webb telescope scheduled for launch around 2008 to 2010). Their least expensive hexapod, with software and a controller is more than $50K. This device supports about 45 pounds and can resolve 3 microns. Since part of our mission and objective is to find a relatively inexpensive and feasible solution, we looked at alternatives. I understand that the PI catalog is on-line at:

www.pi.ws

We reviewed a possible solution under $15K that, we believe, has sufficient range and can support about 10 pounds. I don't know the weight of your camera. Their solution is called rotation, tip and tilt, which could be called roll, pitch and yaw. This solution would involve, a rotation stage (7-60 and 7-61 of the catalog) and a tip/tilt stage (7-63).

We are also in the process of putting together a comprehensive report based upon this memo and our studies. We wanted you to know our thoughts at this point. As you pointed, out the hard part is to determine the direction from here. We obviously need your help with that.

Talk to you soon,
Lou

## Appendix C: Spreadsheet Data

**Spreadsheet 1**

For Spreadsheet 1 see Section 5.2.

**Spreadsheet 2**

See below:

V=Voltage; A=Actuator

| ROLL | PITCH | YAW | V1 | V2 | V3 | V4 | V5 | V6 | Length _A1 | Length _A2 | Length _A3 | Length _A4 | Length _A5 | Length _A6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 48.755 | 2.574 | -83.163 | 1.251 | 1.257 | 1.248 | 1.251 | 1.254 | 1.257 | 2.002 | 2.012 | 1.997 | 2.002 | 2.007 | 2.012 |
| 46.041 | -0.42 | -83.254 | 1.553 | 1.547 | 1.245 | 1.251 | 1.254 | 1.257 | 2.485 | 2.476 | 1.992 | 2.002 | 2.007 | 2.012 |
| 42.997 | -3.583 | -82.842 | 1.862 | 1.862 | 1.248 | 1.251 | 1.254 | 1.257 | 2.979 | 2.979 | 1.997 | 2.002 | 2.007 | 2.012 |
| 39.941 | -6.89 | -82.564 | 2.17 | 2.173 | 1.248 | 1.251 | 1.254 | 1.257 | 3.472 | 3.477 | 1.997 | 2.002 | 2.007 | 2.012 |
| 36.584 | -10.405 | -82.175 | 2.487 | 2.484 | 1.245 | 1.251 | 1.254 | 1.257 | 3.979 | 3.975 | 1.992 | 2.002 | 2.007 | 2.012 |
| 48.657 | 2.386 | -83.557 | 1.251 | 1.257 | 1.248 | 1.251 | 1.254 | 1.257 | 2.002 | 2.012 | 1.997 | 2.002 | 2.007 | 2.012 |
| 47.48 | 6.355 | -83.3 | 1.251 | 1.257 | 1.55 | 1.547 | 1.254 | 1.257 | 2.002 | 2.012 | 2.48 | 2.476 | 2.007 | 2.012 |
| 46.09 | 10.5 | -83.388 | 1.251 | 1.257 | 1.868 | 1.862 | 1.254 | 1.257 | 2.002 | 2.012 | 2.988 | 2.979 | 2.007 | 2.012 |
| 44.632 | 14.849 | -83.635 | 1.251 | 1.257 | 2.176 | 2.173 | 1.254 | 1.257 | 2.002 | 2.012 | 3.481 | 3.477 | 2.007 | 2.012 |
| 43.045 | 19.351 | -83.833 | 1.251 | 1.257 | 2.487 | 2.487 | 1.254 | 1.257 | 2.002 | 2.012 | 3.979 | 3.979 | 2.007 | 2.012 |
| 48.685 | 2.581 | -83.095 | 1.251 | 1.257 | 1.248 | 1.251 | 1.254 | 1.257 | 2.002 | 2.012 | 1.997 | 2.002 | 2.007 | 2.012 |
| 52.683 | 1.595 | -83.563 | 1.251 | 1.257 | 1.248 | 1.251 | 1.547 | 1.544 | 2.002 | 2.012 | 1.997 | 2.002 | 2.476 | 2.471 |
| 57.168 | 0.643 | -83.67 | 1.251 | 1.257 | 1.248 | 1.251 | 1.862 | 1.855 | 2.002 | 2.012 | 1.997 | 2.002 | 2.979 | 2.969 |
| 61.75 | -0.329 | -83.735 | 1.251 | 1.257 | 1.248 | 1.251 | 2.17 | 2.167 | 2.002 | 2.012 | 1.997 | 2.002 | 3.472 | 3.467 |
| 66.695 | -1.385 | -83.855 | 1.251 | 1.257 | 1.248 | 1.251 | 2.487 | 2.484 | 2.002 | 2.012 | 1.997 | 2.002 | 3.979 | 3.975 |
| 48.979 | 2.392 | -83.461 | 1.254 | 1.257 | 1.248 | 1.251 | 1.254 | 1.257 | 2.007 | 2.012 | 1.997 | 2.002 | 2.007 | 2.012 |

**Spreadsheet 2 - Evaluation of INS, based Repeated Hexapod Positions (Test SO_2)**

**Spreadsheet 3**

See below:

V=Voltage; A=Actuator

| ROLL | PITCH | YAW | V1 | V2 | V3 | V4 | V5 | V6 | Length _A1 | Length _A2 | Length _A3 | Length _A4 | Length _A5 | Length _A6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 48.846 | 2.539 | -83.426 | 1.251 | 1.257 | 1.248 | 1.251 | 1.254 | 1.257 | 2.002 | 2.012 | 1.997 | 2.002 | 2.007 | 2.012 |
| 46.005 | -0.399 | -83.309 | 1.553 | 1.544 | 1.248 | 1.251 | 1.257 | 1.26 | 2.485 | 2.471 | 1.997 | 2.002 | 2.012 | 2.017 |
| 42.978 | -3.673 | -82.885 | 1.862 | 1.862 | 1.248 | 1.251 | 1.254 | 1.26 | 2.979 | 2.979 | 1.997 | 2.002 | 2.007 | 2.017 |
| 39.905 | -6.959 | -82.543 | 2.17 | 2.17 | 1.248 | 1.251 | 1.254 | 1.257 | 3.472 | 3.472 | 1.997 | 2.002 | 2.007 | 2.012 |
| 36.509 | -10.433 | -82.273 | 2.487 | 2.484 | 1.248 | 1.251 | 1.254 | 1.26 | 3.979 | 3.975 | 1.997 | 2.002 | 2.007 | 2.017 |
| 48.713 | 2.469 | -83.373 | 1.254 | 1.257 | 1.248 | 1.251 | 1.254 | 1.26 | 2.007 | 2.012 | 1.997 | 2.002 | 2.007 | 2.017 |
| 47.536 | 6.418 | -83.146 | 1.254 | 1.257 | 1.55 | 1.55 | 1.254 | 1.257 | 2.007 | 2.012 | 2.48 | 2.48 | 2.007 | 2.012 |
| 46.103 | 10.509 | -83.548 | 1.254 | 1.257 | 1.862 | 1.862 | 1.254 | 1.26 | 2.007 | 2.012 | 2.979 | 2.979 | 2.007 | 2.017 |
| 44.654 | 14.84 | -83.724 | 1.254 | 1.257 | 2.176 | 2.176 | 1.257 | 1.257 | 2.007 | 2.012 | 3.481 | 3.481 | 2.012 | 2.012 |
| 42.993 | 19.326 | -84.086 | 1.254 | 1.257 | 2.487 | 2.487 | 1.254 | 1.26 | 2.007 | 2.012 | 3.979 | 3.979 | 2.007 | 2.017 |
| 48.755 | 2.532 | -83.071 | 1.254 | 1.257 | 1.245 | 1.254 | 1.254 | 1.26 | 2.007 | 2.012 | 1.992 | 2.007 | 2.007 | 2.017 |
| 52.689 | 1.693 | -83.31 | 1.254 | 1.257 | 1.245 | 1.251 | 1.547 | 1.544 | 2.007 | 2.012 | 1.992 | 2.002 | 2.476 | 2.471 |
| 57.263 | 0.636 | -83.44 | 1.254 | 1.257 | 1.245 | 1.254 | 1.865 | 1.859 | 2.007 | 2.012 | 1.992 | 2.007 | 2.983 | 2.974 |
| 61.722 | -0.455 | -83.957 | 1.254 | 1.257 | 1.245 | 1.254 | 2.173 | 2.167 | 2.007 | 2.012 | 1.992 | 2.007 | 3.477 | 3.467 |
| 66.591 | -1.567 | -84.105 | 1.254 | 1.257 | 1.245 | 1.251 | 2.484 | 2.484 | 2.007 | 2.012 | 1.992 | 2.002 | 3.975 | 3.975 |
| 48.902 | 2.414 | -83.478 | 1.254 | 1.257 | 1.245 | 1.254 | 1.257 | 1.254 | 2.007 | 2.012 | 1.992 | 2.007 | 2.012 | 2.007 |

**Spreadsheet 3 - Evaluation of INS, based Repeated Hexapod Positions (Test SO_3)**

**Spreadsheet 4**

V=Voltage; A=Actuator

| ROLL | PITCH | YAW | V1 | V2 | V3 | V4 | V5 | V6 | Length A1 | Length A2 | Length A3 | Length A4 | Length A5 | Length A6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 48.818 | 2.539 | -83.227 | 1.254 | 1.257 | 1.245 | 1.251 | 1.257 | 1.254 | 2.007 | 2.012 | 1.992 | 2.002 | 2.012 | 2.007 |
| 45.731 | -0.825 | -83.272 | 1.59 | 1.578 | 1.245 | 1.251 | 1.257 | 1.254 | 2.544 | 2.524 | 1.992 | 2.002 | 2.012 | 2.007 |
| 42.827 | -3.78 | -82.937 | 1.883 | 1.88 | 1.245 | 1.251 | 1.257 | 1.254 | 3.013 | 3.008 | 1.992 | 2.002 | 2.012 | 2.007 |
| 39.709 | -7.073 | -82.574 | 2.194 | 2.191 | 1.245 | 1.251 | 1.257 | 1.257 | 3.511 | 3.506 | 1.992 | 2.002 | 2.012 | 2.012 |
| 36.347 | -10.613 | -82.023 | 2.509 | 2.505 | 1.245 | 1.251 | 1.257 | 1.257 | 4.014 | 4.009 | 1.992 | 2.002 | 2.012 | 2.012 |
| 48.895 | 2.715 | -83.306 | 1.236 | 1.236 | 1.245 | 1.251 | 1.257 | 1.254 | 1.978 | 1.978 | 1.992 | 2.002 | 2.012 | 2.007 |
| 47.444 | 6.825 | -83.272 | 1.254 | 1.254 | 1.584 | 1.578 | 1.257 | 1.257 | 2.007 | 2.007 | 2.534 | 2.524 | 2.012 | 2.012 |
| 46.151 | 10.931 | -83.391 | 1.254 | 1.254 | 1.889 | 1.883 | 1.257 | 1.257 | 2.007 | 2.007 | 3.022 | 3.013 | 2.012 | 2.012 |
| 44.656 | 15.148 | -83.708 | 1.254 | 1.254 | 2.194 | 2.194 | 1.257 | 1.257 | 2.007 | 2.007 | 3.511 | 3.511 | 2.012 | 2.012 |
| 42.913 | 19.58 | -83.877 | 1.254 | 1.254 | 2.512 | 2.509 | 1.257 | 1.254 | 2.007 | 2.007 | 4.019 | 4.014 | 2.012 | 2.007 |
| 48.909 | 2.386 | -83.108 | 1.254 | 1.254 | 1.227 | 1.236 | 1.257 | 1.257 | 2.007 | 2.007 | 1.963 | 1.978 | 2.012 | 2.012 |
| 53.025 | 1.615 | -83.508 | 1.254 | 1.254 | 1.251 | 1.245 | 1.566 | 1.559 | 2.007 | 2.007 | 2.002 | 1.992 | 2.505 | 2.495 |
| 57.457 | 0.524 | -83.65 | 1.254 | 1.254 | 1.251 | 1.248 | 1.88 | 1.877 | 2.007 | 2.007 | 2.002 | 1.997 | 3.008 | 3.003 |
| 62.003 | -0.468 | -83.899 | 1.254 | 1.254 | 1.251 | 1.245 | 2.191 | 2.188 | 2.007 | 2.007 | 2.002 | 1.992 | 3.506 | 3.501 |
| 66.823 | -1.504 | -84.216 | 1.254 | 1.254 | 1.251 | 1.248 | 2.505 | 2.502 | 2.007 | 2.007 | 2.002 | 1.997 | 4.009 | 4.004 |
| 48.566 | 2.441 | -83.29 | 1.254 | 1.254 | 1.251 | 1.245 | 1.236 | 1.239 | 2.007 | 2.007 | 2.002 | 1.992 | 1.978 | 1.982 |

**Spreadsheet 4 - Evaluation of INS, based Repeated Hexapod Positions (Test SO_11)**

**Spreadsheet 5**

See below:

V=Voltage; A=Actuator

| ROLL | PITCH | YAW | V1 | V2 | V3 | V4 | V5 | V6 | Length _A1 | Length _A2 | Length _A3 | Length _A4 | Length _A5 | Length _A6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 48.573 | 2.547 | -83.407 | 1.254 | 1.254 | 1.251 | 1.248 | 1.236 | 1.239 | 2.007 | 2.007 | 2.002 | 1.997 | 1.978 | 1.982 |
| 45.579 | -0.58 | -83.03 | 1.572 | 1.569 | 1.251 | 1.248 | 1.236 | 1.239 | 2.515 | 2.51 | 2.002 | 1.997 | 1.978 | 1.982 |
| 42.559 | -3.794 | -83.11 | 1.883 | 1.883 | 1.251 | 1.248 | 1.248 | 1.239 | 3.013 | 3.013 | 2.002 | 1.997 | 1.997 | 1.982 |
| 39.431 | -7.079 | -82.707 | 2.191 | 2.191 | 1.251 | 1.245 | 1.248 | 1.239 | 3.506 | 3.506 | 2.002 | 1.992 | 1.997 | 1.982 |
| 36.038 | -10.582 | -82.186 | 2.512 | 2.505 | 1.251 | 1.248 | 1.248 | 1.239 | 4.019 | 4.009 | 2.002 | 1.997 | 1.997 | 1.982 |
| 48.643 | 2.652 | -83.693 | 1.236 | 1.236 | 1.251 | 1.245 | 1.248 | 1.239 | 1.978 | 1.978 | 2.002 | 1.992 | 1.997 | 1.982 |
| 47.253 | 6.695 | -83.593 | 1.254 | 1.257 | 1.566 | 1.566 | 1.248 | 1.239 | 2.007 | 2.012 | 2.505 | 2.505 | 1.997 | 1.982 |
| 45.843 | 10.975 | -83.52 | 1.254 | 1.257 | 1.883 | 1.883 | 1.248 | 1.239 | 2.007 | 2.012 | 3.013 | 3.013 | 1.997 | 1.982 |
| 44.373 | 15.175 | -83.796 | 1.254 | 1.257 | 2.2 | 2.191 | 1.248 | 1.239 | 2.007 | 2.012 | 3.521 | 3.506 | 1.997 | 1.982 |
| 42.779 | 19.626 | -84.341 | 1.254 | 1.257 | 2.509 | 2.509 | 1.248 | 1.239 | 2.007 | 2.012 | 4.014 | 4.014 | 1.997 | 1.982 |
| 48.622 | 2.427 | -83.2 | 1.254 | 1.257 | 1.227 | 1.23 | 1.248 | 1.239 | 2.007 | 2.012 | 1.963 | 1.968 | 1.997 | 1.982 |
| 52.858 | 1.707 | -83.354 | 1.254 | 1.257 | 1.251 | 1.254 | 1.566 | 1.562 | 2.007 | 2.012 | 2.002 | 2.007 | 2.505 | 2.5 |
| 57.5 | 0.671 | -83.479 | 1.254 | 1.257 | 1.251 | 1.254 | 1.88 | 1.88 | 2.007 | 2.012 | 2.002 | 2.007 | 3.008 | 3.008 |
| 62.081 | -0.44 | -83.666 | 1.254 | 1.257 | 1.251 | 1.254 | 2.191 | 2.185 | 2.007 | 2.012 | 2.002 | 2.007 | 3.506 | 3.496 |
| 66.924 | -1.462 | -83.945 | 1.254 | 1.257 | 1.248 | 1.254 | 2.505 | 2.502 | 2.007 | 2.012 | 1.997 | 2.007 | 4.009 | 4.004 |
| 48.566 | 2.574 | -83.109 | 1.254 | 1.257 | 1.251 | 1.254 | 1.236 | 1.239 | 2.007 | 2.012 | 2.002 | 2.007 | 1.978 | 1.982 |

**Spreadsheet 5 - Evaluation of INS, based Repeated Hexapod Positions (Test SO_12)**

**Spreadsheet 6**

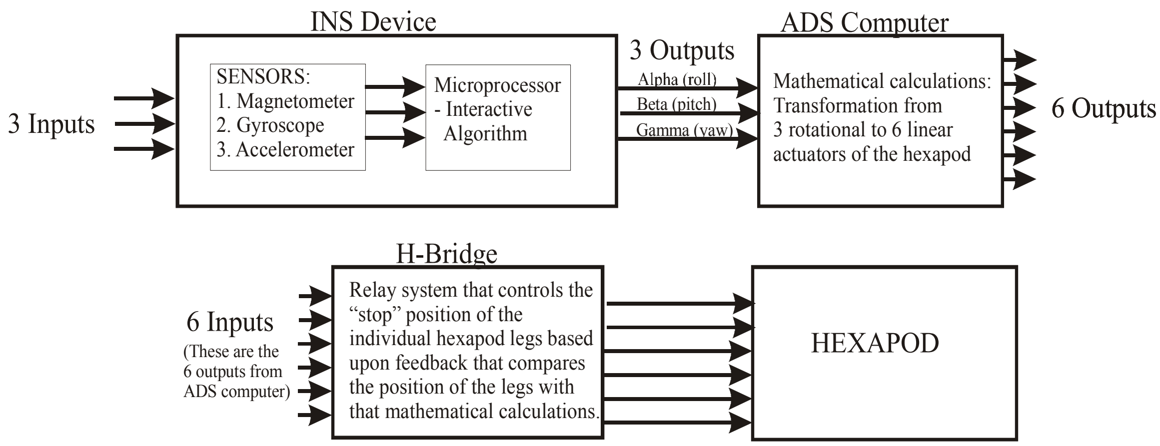
See below:

V=Voltage; A=Actuator

| ROLL | PITCH | YAW | V1 | V2 | V3 | V4 | V5 | V6 | Length A1 | Length A2 | Length A3 | Length A4 | Length A5 | Length A6 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 48.734 | 2.701 | -83.248 | 1.254 | 1.257 | 1.251 | 1.254 | 1.254 | 1.245 | 2.007 | 2.012 | 2.002 | 2.007 | 2.007 | 1.992 |
| 45.831 | -0.406 | -83.013 | 1.569 | 1.566 | 1.251 | 1.254 | 1.254 | 1.245 | 2.51 | 2.505 | 2.002 | 2.007 | 2.007 | 1.992 |
| 42.685 | -3.71 | -82.953 | 1.883 | 1.883 | 1.251 | 1.251 | 1.254 | 1.245 | 3.013 | 3.013 | 2.002 | 2.002 | 2.007 | 1.992 |
| 39.541 | -7.103 | -82.662 | 2.194 | 2.188 | 1.251 | 1.254 | 1.254 | 1.245 | 3.511 | 3.501 | 2.002 | 2.007 | 2.007 | 1.992 |
| 36.124 | -10.582 | -82.133 | 2.509 | 2.505 | 1.251 | 1.254 | 1.254 | 1.245 | 4.014 | 4.009 | 2.002 | 2.007 | 2.007 | 1.992 |
| 48.664 | 2.783 | -83.309 | 1.233 | 1.239 | 1.251 | 1.254 | 1.254 | 1.245 | 1.973 | 1.982 | 2.002 | 2.007 | 2.007 | 1.992 |
| 47.457 | 6.814 | -83.497 | 1.254 | 1.239 | 1.566 | 1.569 | 1.251 | 1.245 | 2.007 | 1.982 | 2.505 | 2.51 | 2.002 | 1.992 |
| 46.049 | 10.984 | -83.619 | 1.254 | 1.239 | 1.88 | 1.886 | 1.254 | 1.245 | 2.007 | 1.982 | 3.008 | 3.018 | 2.007 | 1.992 |
| 44.516 | 15.201 | -84.198 | 1.254 | 1.239 | 2.197 | 2.191 | 1.254 | 1.245 | 2.007 | 1.982 | 3.516 | 3.506 | 2.007 | 1.992 |
| 42.859 | 19.697 | -84.521 | 1.254 | 1.239 | 2.509 | 2.512 | 1.254 | 1.245 | 2.007 | 1.982 | 4.014 | 4.019 | 2.007 | 1.992 |
| 48.937 | 2.42 | -83.337 | 1.254 | 1.239 | 1.227 | 1.23 | 1.254 | 1.245 | 2.007 | 1.982 | 1.963 | 1.968 | 2.007 | 1.992 |
| 53.047 | 1.672 | -83.519 | 1.254 | 1.239 | 1.251 | 1.254 | 1.569 | 1.559 | 2.007 | 1.982 | 2.002 | 2.007 | 2.51 | 2.495 |
| 57.497 | 0.734 | -83.512 | 1.254 | 1.239 | 1.251 | 1.254 | 1.88 | 1.877 | 2.007 | 1.982 | 2.002 | 2.007 | 3.008 | 3.003 |
| 62.177 | -0.322 | -83.779 | 1.254 | 1.239 | 1.248 | 1.254 | 2.191 | 2.188 | 2.007 | 1.982 | 1.997 | 2.007 | 3.506 | 3.501 |
| 67.006 | -1.378 | -83.981 | 1.254 | 1.239 | 1.251 | 1.254 | 2.502 | 2.502 | 2.007 | 1.982 | 2.002 | 2.007 | 4.004 | 4.004 |
| 48.636 | 2.491 | -83.455 | 1.254 | 1.239 | 1.248 | 1.254 | 1.236 | 1.236 | 2.007 | 1.982 | 1.997 | 2.007 | 1.978 | 1.978 |

**Spreadsheet 6 - Evaluation of INS, based Repeated Hexapod Positions (Test SO_13)**

## Appendix D: Schematic Overview




Note: GPS has been separated out, therefore it is not shown.

Figure1 - Stabilization of Platform for Imaging Device

## Appendix E: Selected Slides from ADS Power Point Presentation (June 2002)

# *HEXAPOD PROJECT*

GOALS AND OBJECTIVES SO FAR:

1. DEFINED AND DESIGNED NEW ACTUATOR DRIVERS TO COMPLIMENT THE FLEXMOTION BOARD AND DRIVERS.
2. PORTABILITY ISSUES -- LAPTOP APPROACH WITH PCMCIA MODULE AND INTERFACES.
3. GPS ANTENNA ISSUES RESOLVED. ANTENNA HAS TO BE TESTED.
4. OPTIMISATION OF COST AND SPEED DESIGN ISSUES -- USING MICROCONTROLLERS & SOLID STATE SWITCHING (H-BRIDGE)

**SLIDE 1**

# *HEXAPOD PROJECT*

GOALS AND OBJECTIVES SO FAR: (CONTINUED)

5. INS TO HEXAPOD MATHEMATICAL RELATIONSHIPS USING GPS AND NAVIGATION INPUTS.
6. LABVIEW SOFTWARE DEVELOPED FOR THE H-BRIDGE ACTUATOR APPROACH.
7. INTELLECTUAL PROPERTY ISSUES RELATING TO DESIGN - COST ENHANCEMENTS AND COMMERCIALIZTION & LICENSING CONSIDERATIONS.
8. WORKING DEMONSTRATIONS: FLEXMOTION AND H-BRIDGE HEXAPOD DRIVERS.
9. WORKING DEMONSTRATIONS: GPS ANTENNAS AND SPECS. CMIGITS INTERFACE.

**SLIDE 2**

## *HEXAPOD PROJECT*

GOALS AND OBJECTIVES SO FAR:

1. DEFINED AND DESIGNED NEW ACTUATOR DRIVERS TO COMPLIMENT THE FLEXMOTION BOARD AND DRIVERS.

2. PORTABILITY ISSUES -- LAPTOP APPROACH WITH PCMCIA MODULE AND INTERFACES.

3. GPS ANTENNA ISSUES RESOLVED. ANTENNA HAS TO BE TESTED.

4. OPTIMISATION OF COST AND SPEED DESIGN ISSUES -- USING MICROCONTROLLERS & SOLID STATE SWITCHING (H-BRIDGE)

**SLIDE 3**

## *HEXAPOD PROJECT*

FLEXMOTION ACTUATOR DRIVER:

1. THE CURRENT SET UP OF THE HEXAPOD THAT WAS TRANSFERRED TO ADS INC. BY NASA REQUIRES A NATIONAL INSTRUMENTS FLEXMOTION BOARD INSIDE THE PC WITH OUTSIDE DRIVER CONTROLLER BOXES MANUFACTURED BY -----.

2. THE COST OF THE FLEXMOTION PC MODULE IS $5600.00 AND EACH CONTROLLER ON THE OUTSIDE IS ABOUT $700. THIS RESULTS IN A TOTAL COST OF $9800.00.

3. THE AMOUNT WIRING AND SPACE USED BY THIS APPROACH IS CONSIDERABLE AND IS LESS SUITABLY FOR PORTABILITY AND PLACEMENT IN THE TARGET AREA OF THE AIRCRAFT.

**SLIDE 4**

# *HEXAPOD PROJECT*

ADS H-BRIDGE INNOVATION FOR ACTUATOR MOTION:

1. ADS HAS JUST FABRICATED AND TESTED AN ALTERNATIVE TO THE FLEXMOTION DRIVER. THIS APPROACH UTILISES A COMBINATION OF LATCHES FOR PORT EXPANSIION AND H-BRIDGE DRIVERS TO MOVE THE ACTUATORS.

2. THE RESULTS OF THIS APPROACH ARE NOT FINAL. BUT PERLIMINARY TESTING ARE PROMISING TO REALISE CONSIDERABLE COST, POWER , SPACE SAVING WITH POSSIBILITY OF FASTER NAVIGATION ACQUISTION SPEEDS.

**SLIDE 5**

# *ACTUATOR MOTION DESIGN CONSIDERATIONS*

**Comments on the flexmotion (F) and h-bridge (H) approaches: hexapod**

**1. We believe that the (F) calculates everything before any moves are made from distance and velocity considerations. Acceleration and variable voltages may or may not be factors.**

**2. We could and probably should take the same velocity approach with (H). Since we know the target distance for each actuator and the speed of each actuator, the time to the target can easily be calculated. The pattern needs to change only 6 times as in the approach that Yusuf is taking today.**

**SLIDE 6**

# *ACTUATOR MOTION DESIGN CONSIDERATIONS (cont'd)*

**3. TIME becomes the principle factor. This is similar to the long pulse that results in pulse width modulation of the actuator drive signal.**

**4. Mid-course corrections to TIME can be made be made by comparisons to the place where the actuator is and where it should be. This is in a sense a velocity correction. Patterns or (H) clicks only take place when an actuator has fulfilled its time commitment – that is come to a stop.**

**SLIDE 7**

# *ACTUATOR MOTION DESIGN CONSIDERATIONS (cont'd)*

**5. ADS's current implementation although comparable in speed to the flexmotion device maybe further enhanced by use of solid state switches (possibly Power MOSFETs) and local intelligence using programmable microcontrollers for each leg of the hexapod. This will remove speed as in issue with the software since the calculations and movement ordering time will be insignificant in relation to the movement dynamics and speed of the actuator itself. This will also replace a very expensive and large component in the PC, which will allow use to use laptops or even PDA type of devices with wireless capability.**

**SLIDE 8**

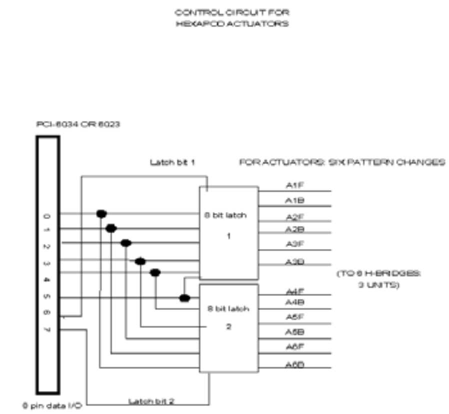
# *HEXAPOD PROJECT*

PORT EXPANSION OF
THE PCI-6034 NI DAQ

THE 8 BITS OF THE PCI-6034 WERE EXPANDED TO 12 BITS BY ADDING LATCHES OUTSIDE.

THE DIAGRAM SHOWS THE SCHEMATIC AND LOGIC MAP OF THE BIT EXPANSIONS MODULE.

THIS MODULE IS DESIGNED TESTED AND WORKING.




H-BRIDGE CODES

| | FOWARD | BACK | STOP | AVOID |
|---|---|---|---|---|
| A1F | 1 | 0 | 1 | 0 |
| A1B | 0 | 1 | 1 | 0 |

**SLIDE 9**

## Appendix F: 3DM-G User Manual

Print out the Manual for the 3DM-G from Microstrain.
www.microstrain.com
phone: 802-862-6629

Manual: MAN-3DGMUser100 Ver1 (Draft) copyright 2003 Microstrain, Inc.